Run-time Assurance for Advanced Propulsion Algorithms

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5th NASA GRC Propulsion Control and Diagnostics Workshop
September 16-17, 2015

Outline

- Motivation & Background
- Run-Time Verification Overview
- Case Study
- Experiment Results
- Conclusion
- Future Work

Motivation & Background

Motivation: Advanced Propulsion Algorithms

- Safety and performance goals for next-gen aircraft have driven the development of increasingly advanced engine control and health management algorithms:
  - Intelligent and autonomous
  - Adaptive, onboard learning, self-tuning and reconfigurable
- Potential to enable:
  - Increased performance
  - Autonomous adaptation to accommodate:
    - Damage and wear
    - Hardware faults (sensors & effectors)
    - Uncertain environmental conditions
- Emerging approach at NASA and industry partners:
  - Real-time onboard models
    - Enable estimation of unmeasured engine parameters
    - Enable estimation-based control
    - Facilitate onboard diagnostic

Motivation: Certification Challenge

- Deployment of **advanced algorithms** require certification to achieve high confidence in their safety.
  - Becoming increasingly difficult and cost-prohibitive using current verification & validation (V&V) practices
  - Complete V&V at design-time for some algorithms may not be feasible
    - Non-determinism or complexity preclude exhaustive testing
    - As a result, complete coverage cannot be achieved

- Problem being addressed
  - Advancements in design-time analysis (formal methods) to provide mathematical proof of the safe execution of highly complex systems.
  - Advancements in run-time verification – using monitors to observe execution of uncertified algorithms to insure system behavior remains constrained within acceptable bounds of stability.

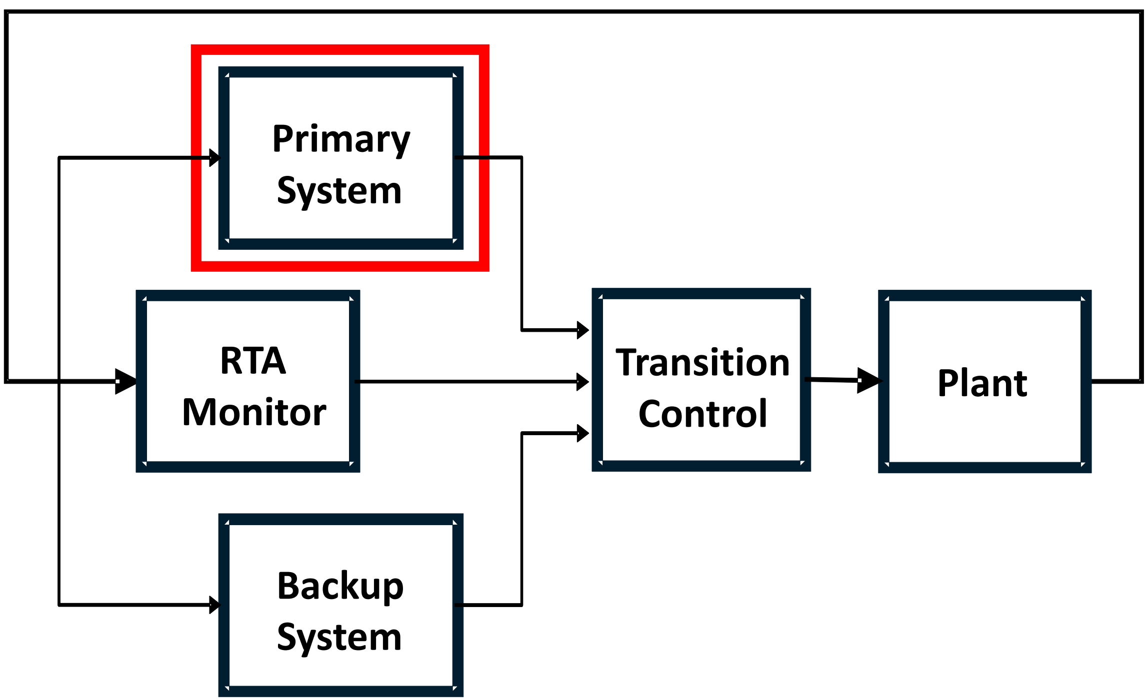
Run-Time Verification

Run-Time Verification Overview

- An analysis approach from computer science
  - Monitors observe execution of a running system (i.e. software program) to detect whether behavior satisfies or violates correctness properties.
  - Used to augment design-time model checking of high-level language programs.
- Application of run-time monitoring to real-time software.
  - Real-time execution enables (upon detection of property violation):
    - Remedial action (e.g. provide an alert, influence subsequent execution) or
    - Enforcement of an expected behavior to avoid violations.
- Recent research investigates application to:
  - Verification of embedded systems (tightly coupled software/hardware)
  - Safety-critical systems
  - Run-time assurance of flight-critical system
  - NASA interest in run-time assurance for advanced engine algorithms

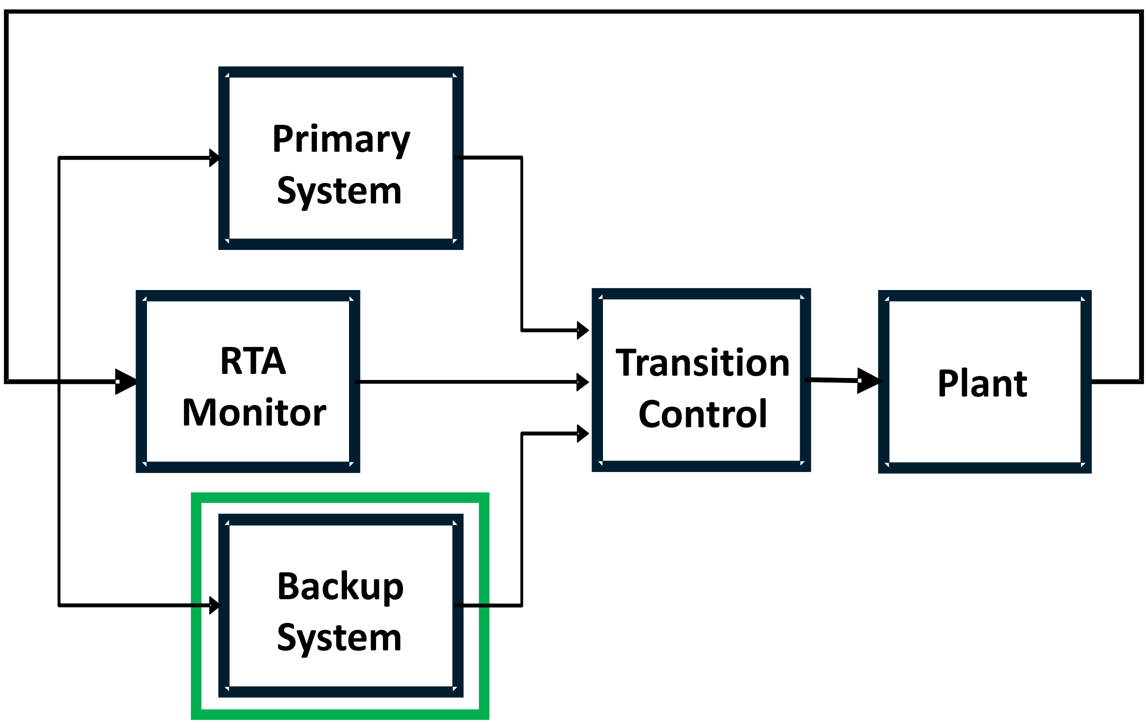
Run-Time Assurance Framework

- Primary System (Advanced)
  - Advanced controller responsible for achieving performance objectives
  - Intelligent, reconfigurable, learning, adaptive, non-deterministic, etc.
  - Enabled at all times under nominal conditions
  - Difficult or costly to fully certify at design time



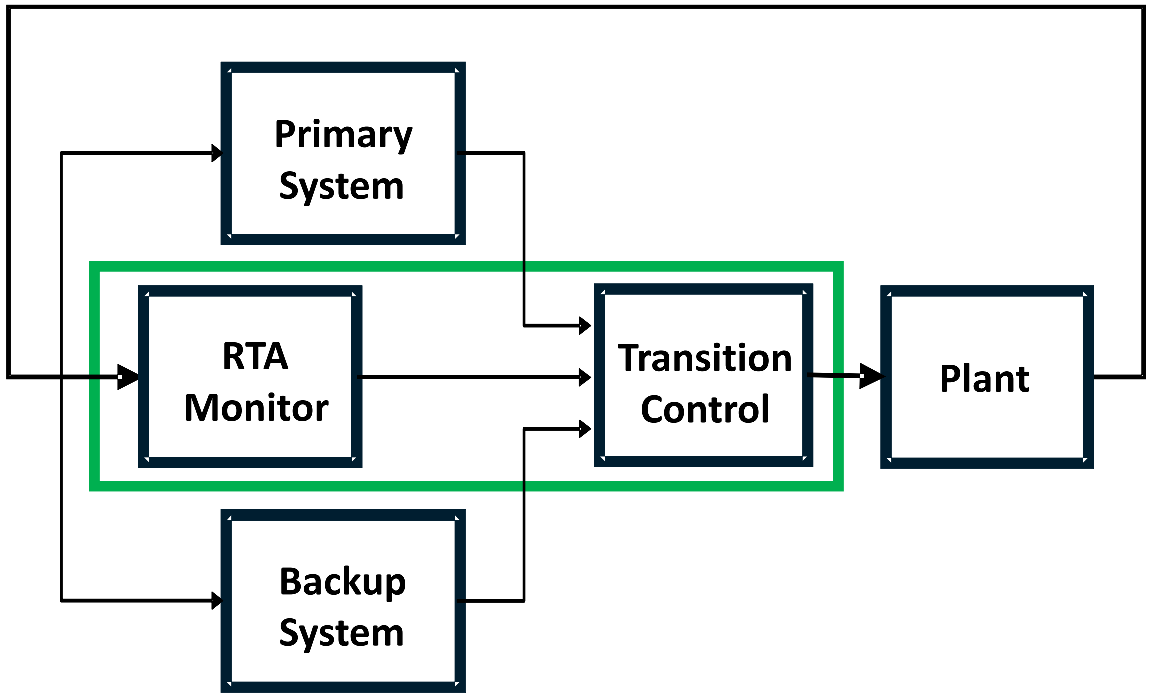
Run-Time Assurance Framework

- Backup System (Fail-Safe)
  - Simplified control system with emphasis on safety rather than performance
  - Does not possess advanced elements that cannot be certified
  - Certified at design-time using traditional methods



Run-Time Assurance Framework

- RTA Monitor & Transition Control
  - Continually monitor overall state of the system
  - Compare against validated representation of safe operating envelope
  - If violation occurs, Transition Controller disables Advanced System and transfers control to Backup System
  - Must be certified at design time



RTA Implementation Issues

- What should be monitored?
  - All states & critical parameters that affect safety of the system
    - Safety limits (structural limits, component limits)
    - Operational limits
    - Performance limits
- How should the switching conditions be defined?
  - When should the switch be activated? How much margin needed?
    - Switch too late – safety could be compromised
    - Switch too early – performance of advanced system could be limited

Case Study: Model-Based Engine Control

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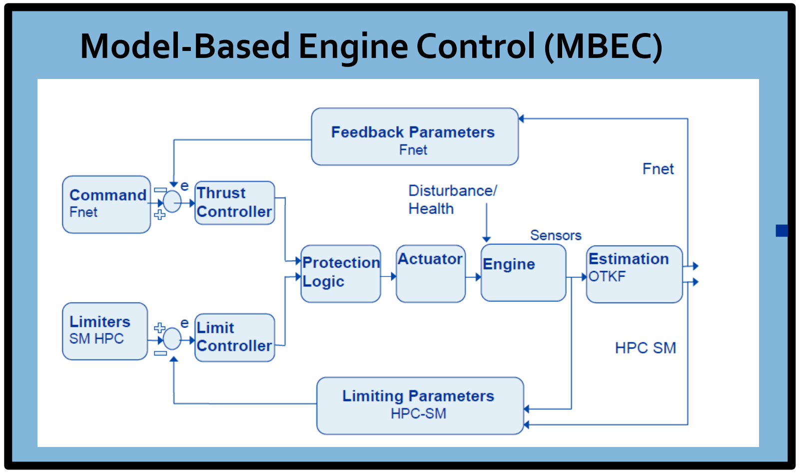
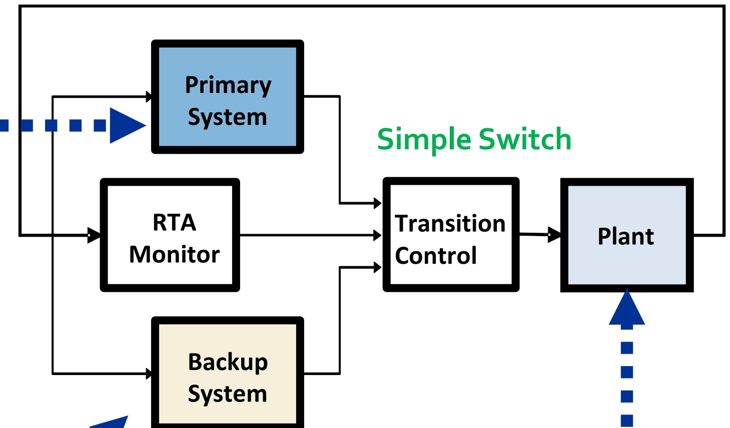
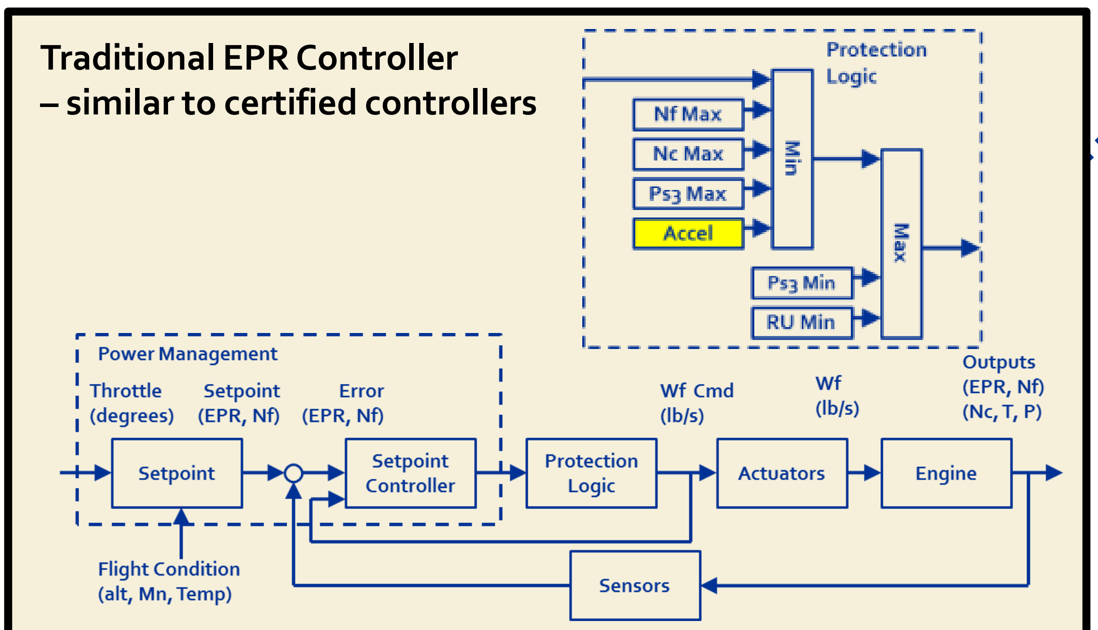
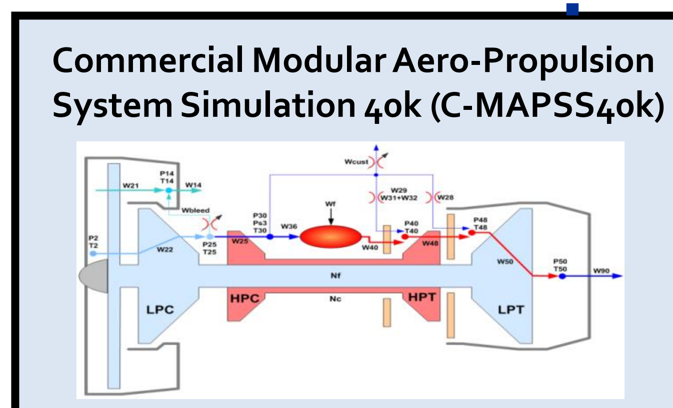
- Investigate application of RTA approach to GRC's Model-Based Engine Control

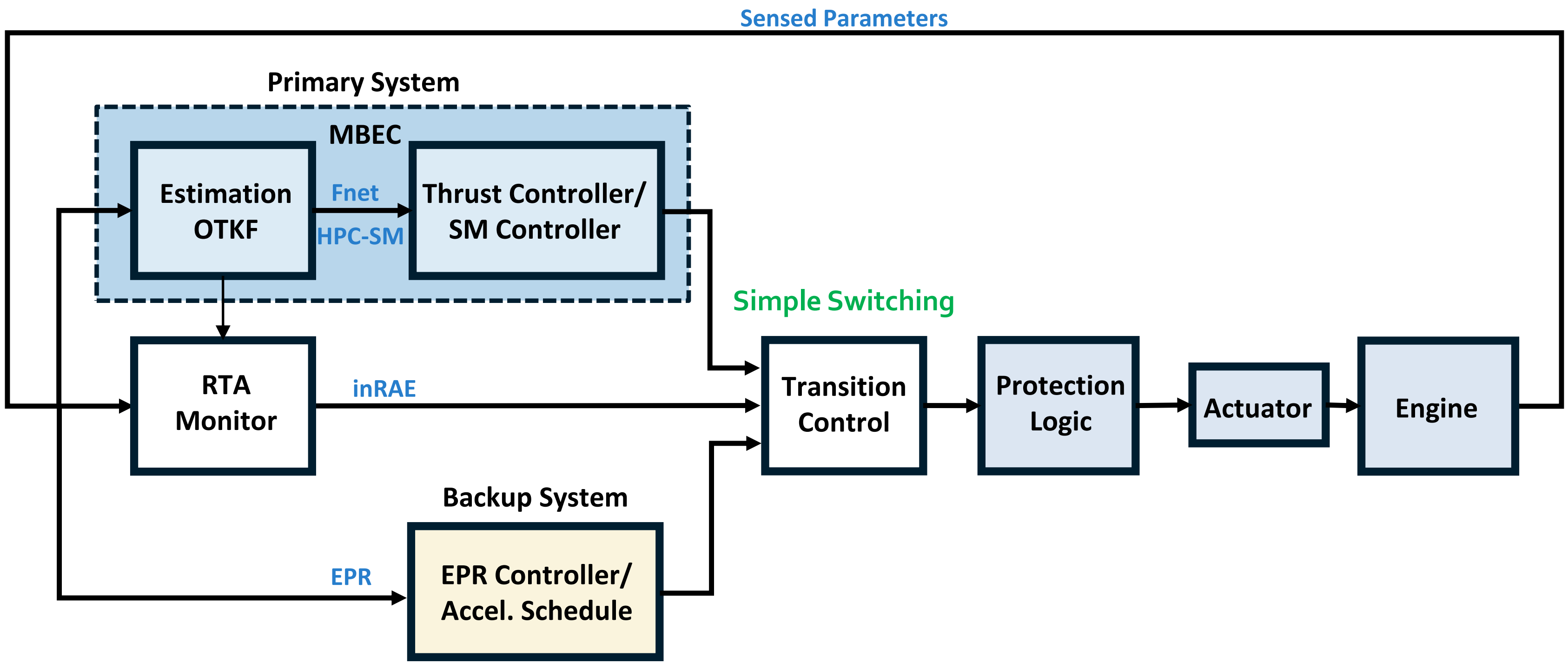








RTA Integrated with Engine Control



- Integrated in a simulation platform under MATLAB/Simulink
- RTA outputs *inRAE* flag to select control mode
  - inRAE = 1 => true => no parameter has violated its limit
  - inRAE = 0 => false => at least one parameter has violated its limit
- Transition Control performs simple switching between the advanced thrust based controller and the backup EPR controller
- Switching the type of stall margin limiter

Monitored States

- Defining Safety Boundaries for this initial study
  - Monitored well-understood engine safety & operational limits
  - Monitored analytical parameters: Kalman filter residuals to assess performance

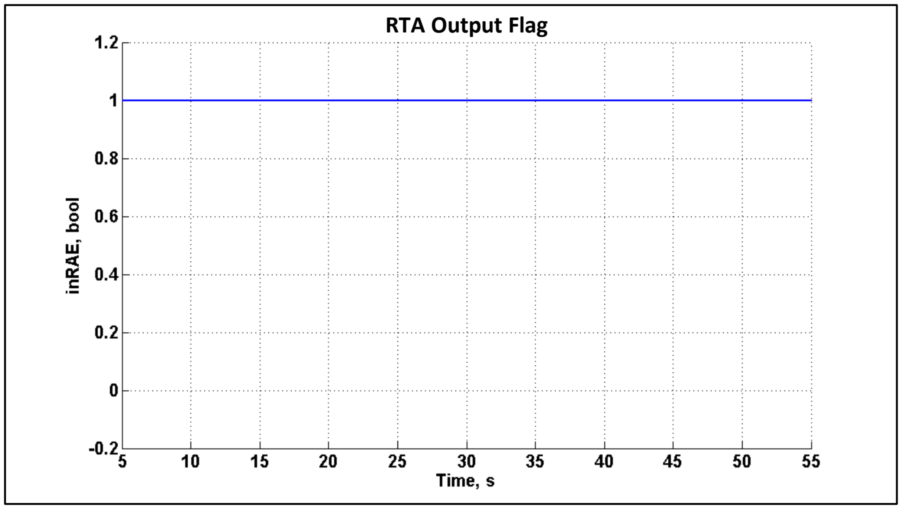
Limited Parameter	**Value**
Safety and Operational Limits	
Fan Speed (Nf)	max = 4200 rpm
Core Speed (Nc)	max=12200 rpm
HPC discharge pressure (Ps3)	max = 433 psi
HPC stall margin (smHPC)	min = 8%
LPC stall margin (smLPC)	min = 6%
RU limit	min = 17%
Kalman Filter Residual Limits (% error)	
Fan speed (Nf)	max = 3%
Core speed (Nc)	max = 3%
HPC discharge temperature (T30)	max = 3%
LPT discharge temperature (T50)	max = 3%
HPC discharge pressure (Ps3)	max = 3%
LPT exit pressure (P50)	max = 3%

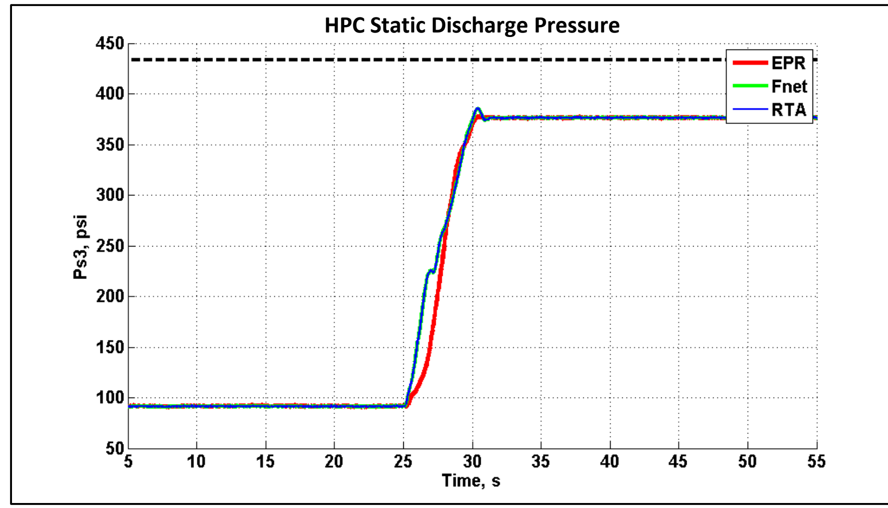
$$\text{Ratio Unit Limit} = \frac{w_f}{P_{S3}}$$

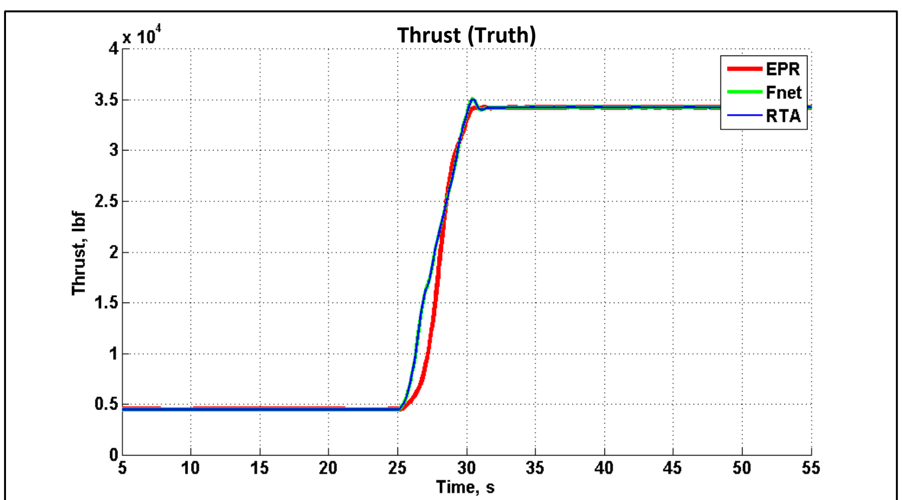
Experimental Results

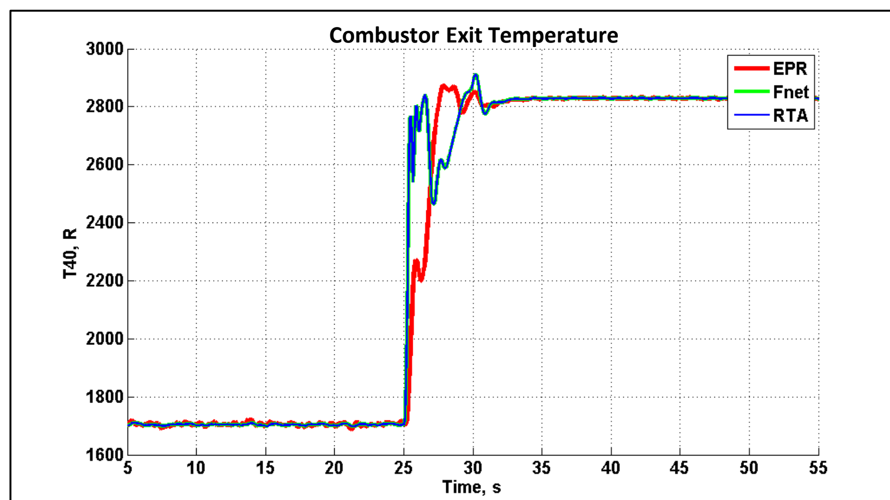
Nominal Experimental Results

- Nominal Take-off
  - PLA increased: 43 to 80 deg. over 5 sec. Initial conditions: Mach 0, altitude 0 ft.
  - RTA maintains operation with Model-based Engine Controller



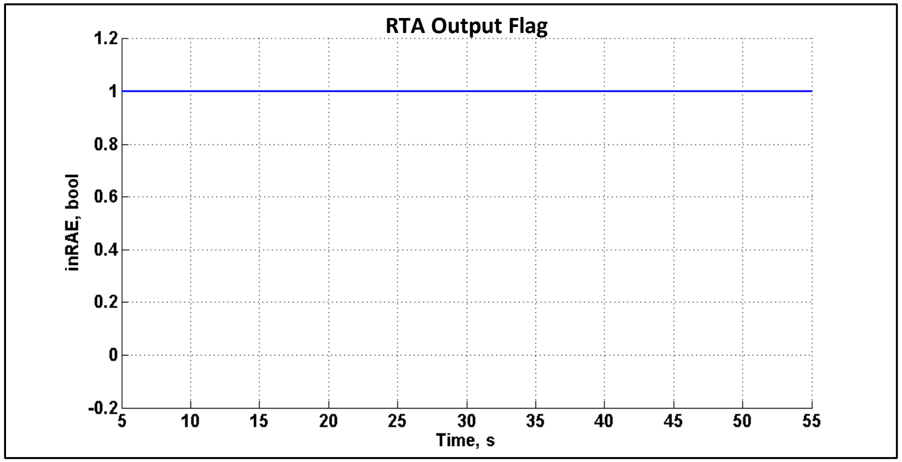


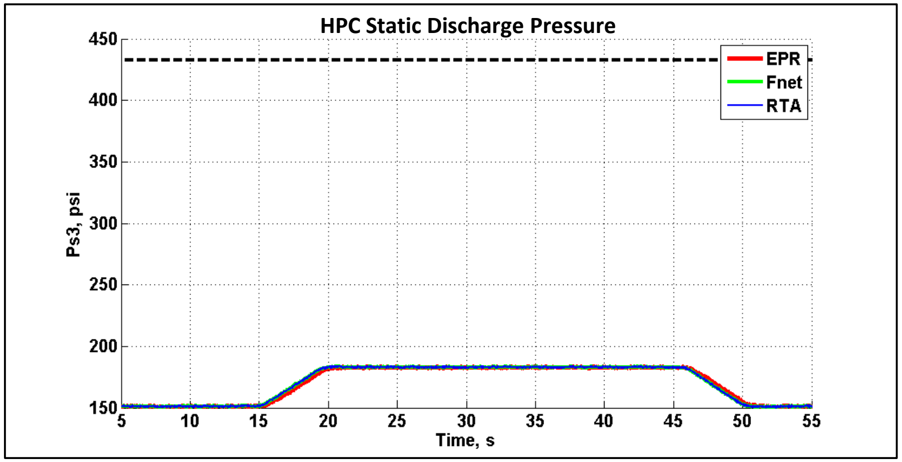


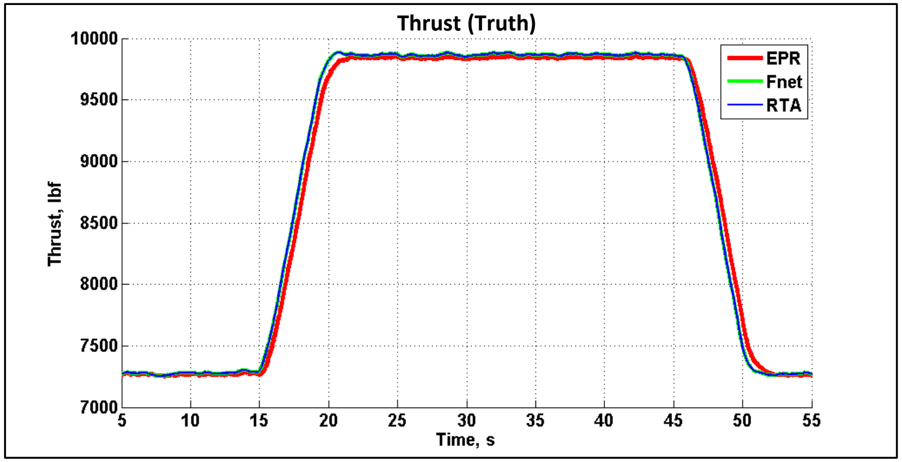


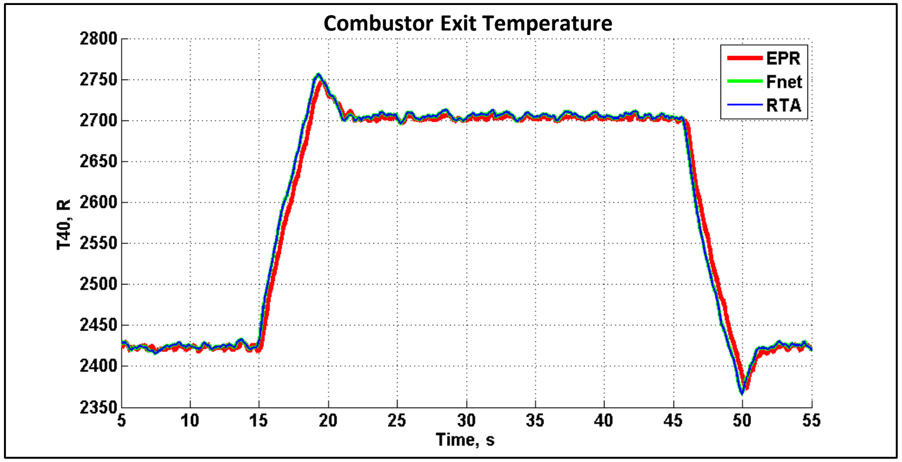
Nominal Experimental Results

- Nominal Cruise
  - PLA increased: 60 to 70 deg. over 5 sec. Initial conditions: Mach 0.7, altitude 30K ft.
  - RTA maintains operation with Model-based Engine Controller



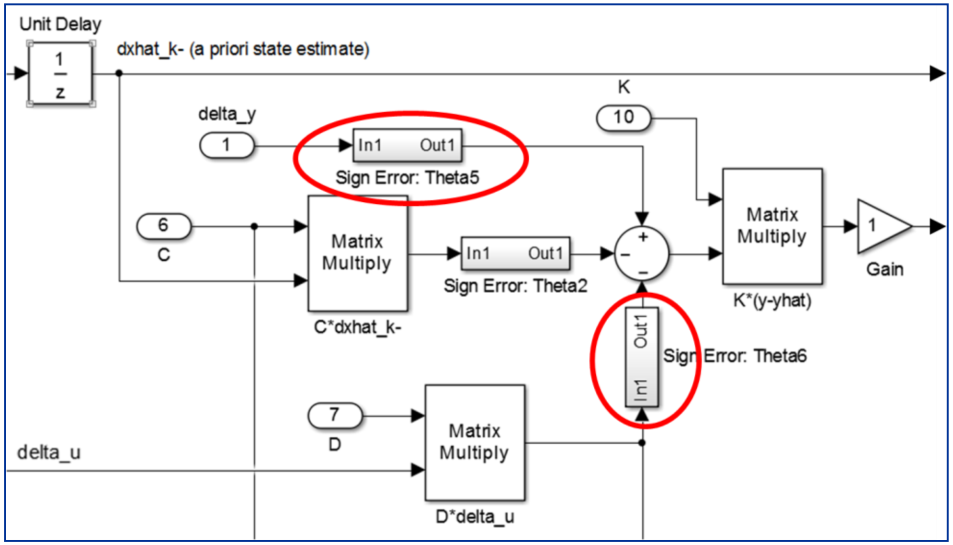






Induced OTKF Fault Experiment

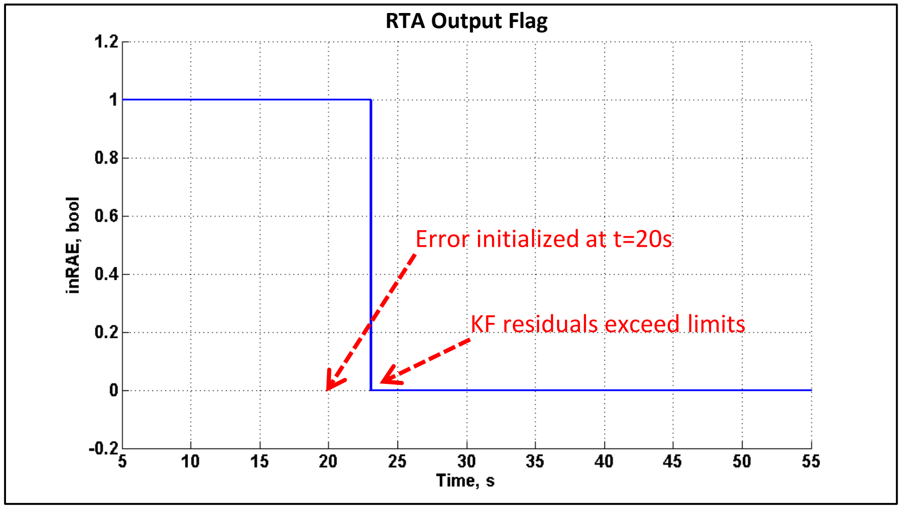
- Seeded error within the OTKF
  - Created sign errors in simulation (e.g. Δy and $D\Delta u$ terms)
  - Result in:
    - Incorrect estimates
    - Poor performance
    - Issues with protection logic

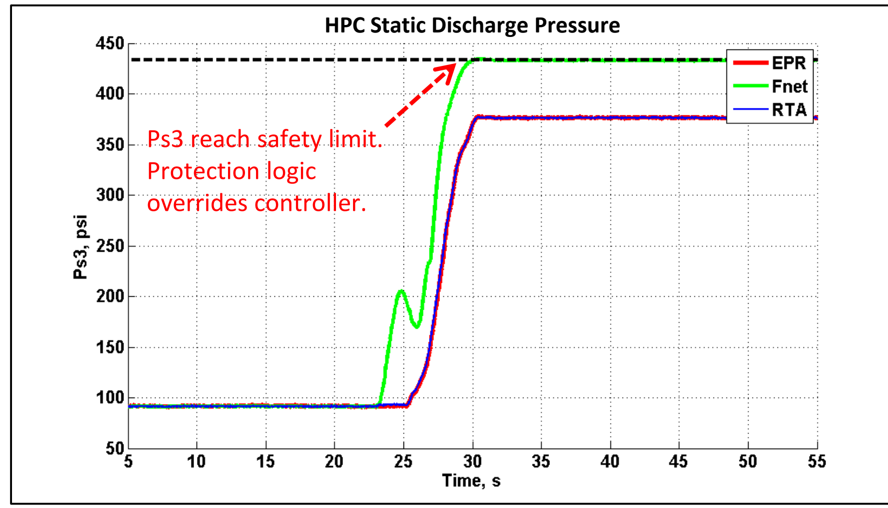


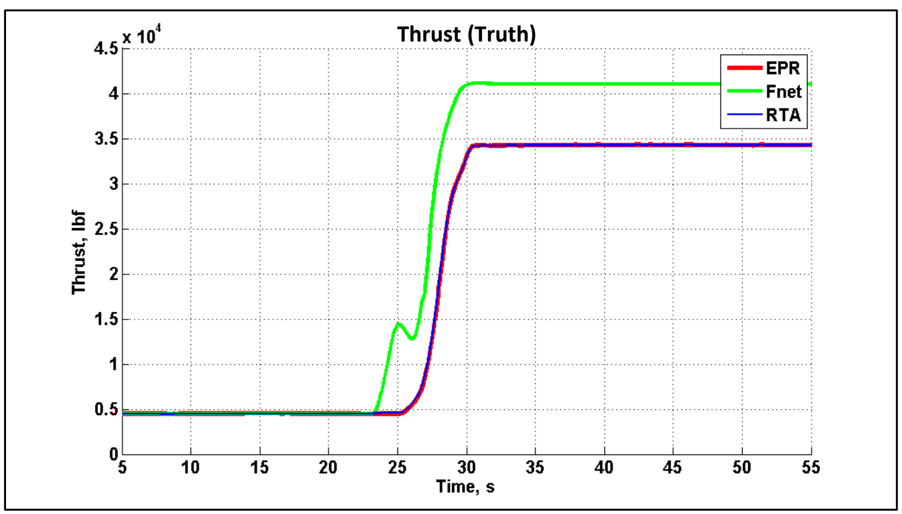
- Operating conditions:
  - Take-off profile
    - PLA linearly increased: 43 to 80 deg. over 5 second period
    - Initial conditions: Mach 0, altitude 0 ft.
  - Cruise operating condition
    - PLA linearly increased: 60 to 70 deg. over a 5 second period
    - Initial conditions: Mach 0.7, altitude 30K ft.

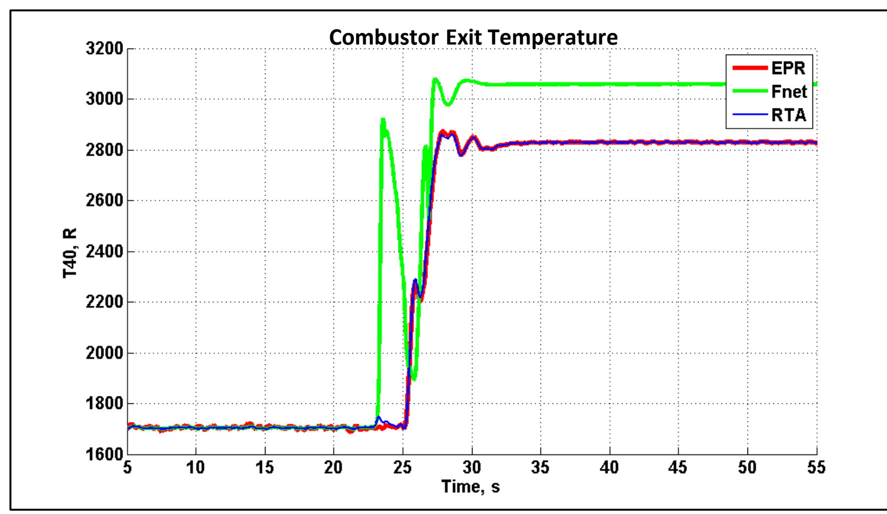
Induced OTKF Fault Experiment

- Seeded error: *Δy* coding error (sign error) introduced @ t = 20 sec during <u>take-off</u>
  - RTA switches to EPR controller @ t = 22 sec 🡐 KF residuals exceed their limits
  - Ps3 reaches safety limit. Protection Logic overrides controller



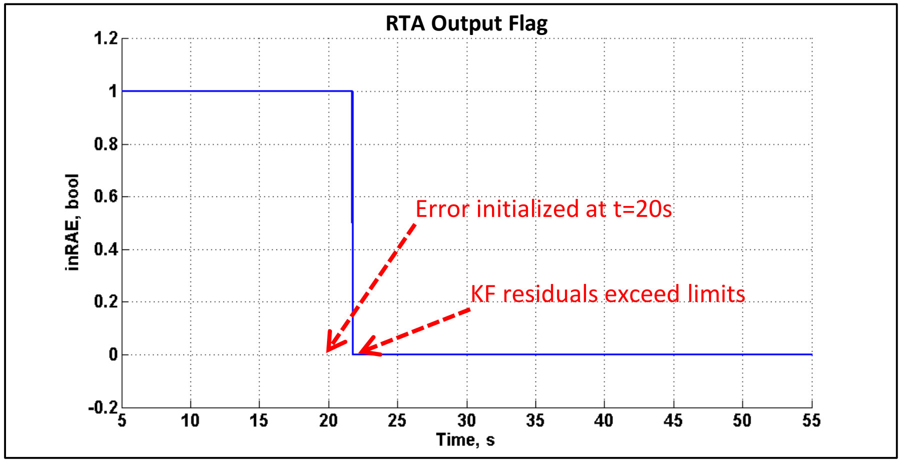


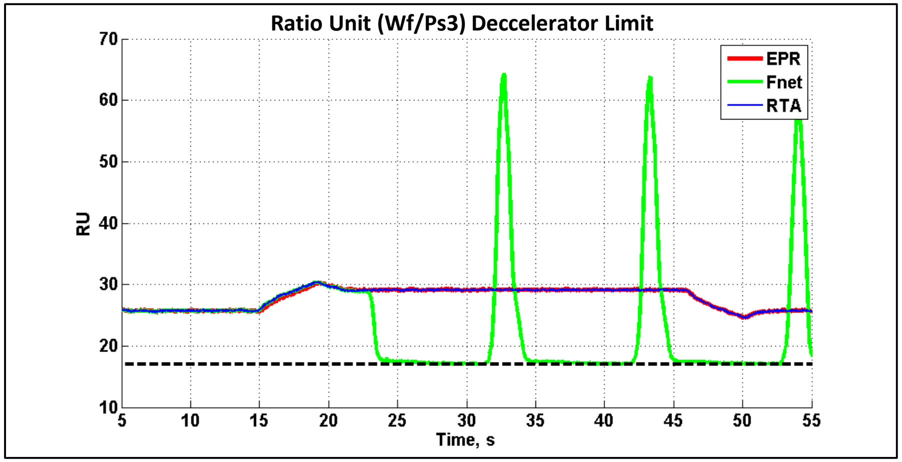


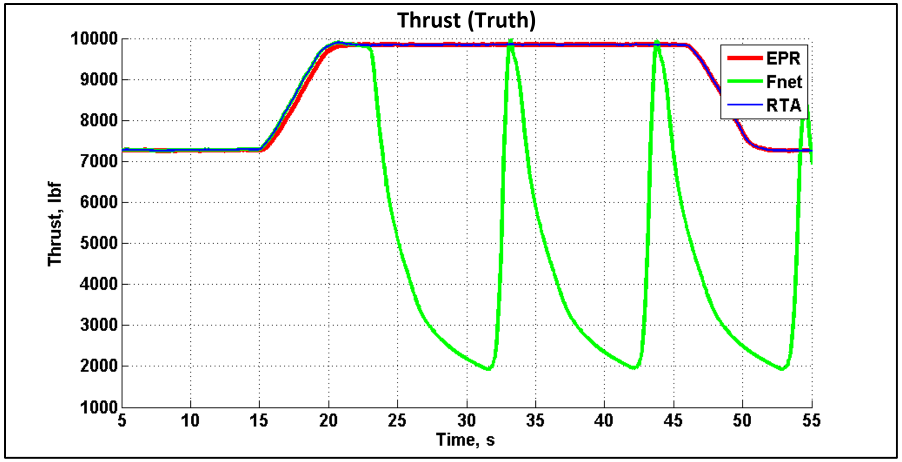


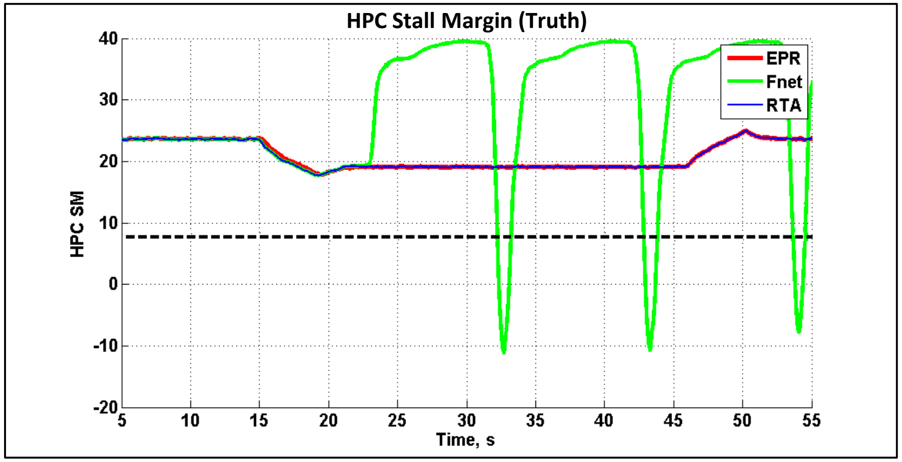
Induced OTKF Fault Experiment

- Seeded error: *Δy* coding error introduced @ t = 20 sec during cruise
  - RTA switches to EPR controller @ t = 22 sec 🡐 KF residuals exceed their limits
  - Alternating control from protection logic elements: RU min. limiter & HPC SM max. limiter









Conclusion

- Provided motivation for pursuit of run-time assurance as a potential means to address certification barrier for advanced propulsion algorithms.
- An overview of run-time monitoring methods was presented.
- A case study was initiated to investigate the feasibility of RTA approach to propulsion control.
- An RTA framework was developed and integrated with NASA's Model-Based Engine Control (MBEC) architecture
- Preliminary experiments and results.

Future Work

- Current:
  - Develop more robust transition logic to replace the simple switching. Ensure stable transition from the advanced controller to the backup controller.
  - Investigate more sophisticated approaches to determination of safety envelope. In addition to current safety, operational & performance limits/conditions.
- Long-term:
  - Investigate a generalized RTA framework for propulsion control monitoring, assurance and assessment.
    - Applicable to other advanced algorithms
    - Scalable to a variety of propulsion types.
  - Engage certification authorities to work towards acceptance of approach.

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